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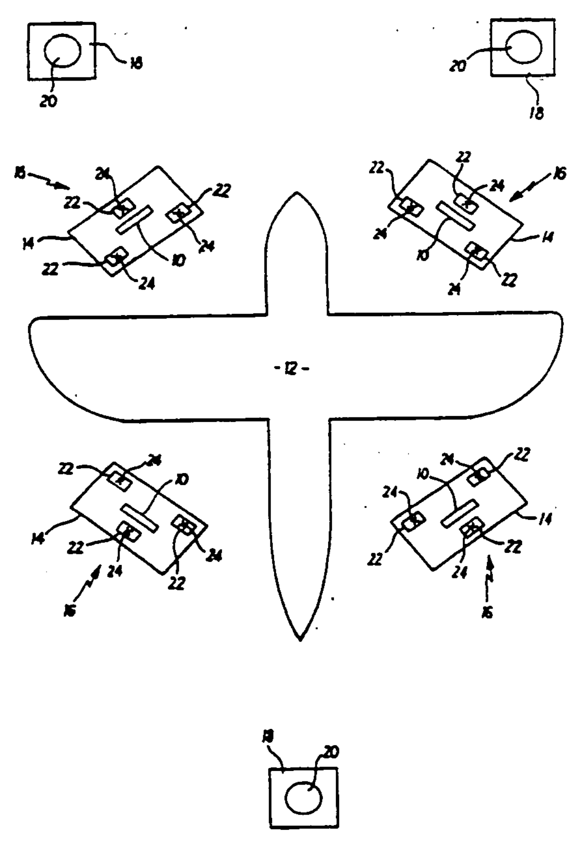
(54) Title: CALIBRATION OF MEASURING APPARATUS

(57) Abstract

Calibration of measuring apparatus such as a co-ordinate measuring machine (CMM) (10) is provided. The CMM (10) is mounted on a pallet (14) which is movable to measuring positions (16) to allow a large object (12) to be measured. Laser trackers (20) at fixed positions (18) track a retro device (22) which can move between three points (24) on the pallet (14). By maintaining the beam as the retro (22) moves around the points (24), and as the pallet (14) moves around the positions (18), the relative positions and orientations of the pallet can be accurately determined, to calibrate the CMM measurements. Movement of the retro (22) creates a notional calibration artefact. Other arrangements described use of a physical calibration artefact.



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Calibration of Measuring Apparatus

The present invention relates to the calibration of measuring apparatus, and in particular to the calibration of apparatus for determining the spatial relationship between two relatively movable components. An example of such apparatus is a co-ordinate measuring machine (CMM) which is used to determine the relationship between the machine and a workpiece for accurately measuring the workpiece or controlling its relationship with other machinery.

In carrying out work on a workpiece, such as manufacturing the workpiece or measuring the workpiece, or assessing its quality or fitness for purpose, it is sometimes necessary to present the workpiece to the machine or present the machine to the workpiece in a variety of different linear or angular positions. Usually the work carried out on the workpiece at the different positions must be accurately related so that all the dimensions produced or measured relate to a common co-ordinate system for the workpiece as a whole. A system of co-ordinates with any number of axes may be used and the system may be orthogonal, cylindrical polar, spherical polar or other.

For example, when measuring features on a workpiece in three dimensions, it is often necessary to have access to many different orthogonal faces of the workpiece or access at various angles to the axes of the machine. A conventional way of achieving this is to use a rotary table with a vertical rotation axis to carry the workpiece. To achieve accuracy one way is to use an accurate and therefore expensive rotary table and to align this to the machine axes very accurately. Alternatively, any misalignment or angular dividing error can be calibrated at all those angles of rotation of the rotary table which are to be used. Because of coning errors of most rotary tables, multiple calibration, rather than accurate alignment, is the preferred method and removes the need for extreme accuracy of the rotary table but still leaves a requirement of very good positional repeatability which means that the rotary table will still be expensive.

With very large workpieces, it is particularly difficult to achieve the required degree of angular accuracy and/or repeatability of the rotary table, since for a given degree of linear accuracy, the angular accuracy must be better in proportion to the increase in the radius. Also for very large workpieces, a rotary table may be prohibitively expensive or impractical.

Our co-pending patent application (Swindell & Pearson reference 4873) describes apparatus for determining the spatial relationship of two relatively movable components. The apparatus comprises means for moving at least one of the components relative to the other into a selected one of a plurality of positions, and means providing effectively for a six point kinematic location of said one component at each of the plurality of positions.

For example, a CMM may have a rotary table on which a workpiece is placed and which can be turned to several measuring positions from which different aspects of the workpiece may be measured. At each location, the pallet has a six point kinematic location.

The techniques described in our co-pending application allow accurate measurement of the workpiece relative to these measuring positions. There remains the problem of calibrating the arrangement and it is this problem to which the present invention is addressed.

The present invention provides apparatus for use in the calibration of measuring apparatus which determines the spatial relationship of two relatively movable components and which comprises means for moving one of

the components relative to the other into a selected one of a plurality of measuring positions, and which further comprises means providing six point kinematic location of the movable components at each of the measuring positions, the calibration apparatus comprising a fixable article fixedly locatable on the movable component, the position of the fixable article being measurable in relation to a fixed position when the movable component occupies any of at least two of the measuring positions, to enable the spatial relationship of those measuring positions to be wholly or partially determined.

The position of the fixable article is preferably measurable in relation to the same fixed points when the movable member is located at any of the measuring positions. The fixable article may be movable between a plurality of positions in relation to the movable component, and be fixedly locatable in each of the said positions. The fixed article may be fixedly locatable on the movable component by means providing six point kinematic location.

The apparatus may further comprise second measuring apparatus operable to determine the spatial relationship of the or each fixed position and the fixable article.

The second measuring apparatus is preferably operable to perform measurement by projecting a beam between the or each fixed position and fixable article when the movable component is located at a measuring position. The beam may be a laser beam. The second measuring apparatus may comprise a laser tracker device and a retro-reflector device for receiving a beam projected from the tracker device. The second measuring apparatus may comprise beam projecting means or beam receiving means movable between the fixed positions, the fixable article comprising beam receiving means or beam projecting means, respectively.

The apparatus may further comprise means for establishing six point kinematic location of the beam projecting or receiving means at each of the fixed positions.

The measuring apparatus being calibrated may be operable to provide measurements between the fixed position and the fixable article. The fixable article may be a calibration artefact defining a sufficient plurality of points for measurement to allow the spatial relation of the movable member and the fixed position to be determined by measurements taken between each point for measurement and the fixed position. The calibration

artefact may define four points for measurement. The calibration artefact may be a tetrahedron, defining a point for measurement at each apex.

The apparatus may comprise level measuring means carried by the movable component and operable to measure rotation of the movable component about at least one horizontal axis. The second measuring apparatus may further comprise means operable to detect rotation of the movable component about a vertical axis.

The apparatus may be operable to determine the spatial relationship between a fixed position and a plurality of points on the movable component defined by a fixable article or articles, the plurality of points being so located on the movable component that for each pair of adjacent measuring positions, there exists at least one point whose spatial relationship relative to the fixed position can be determined when the movable component is located at either measuring position, of the pair, whereby each measuring position may be calibrated with reference to a neighbouring measuring position.

Examples of apparatus embodying the present invention will now be described in more detail, by way of example only, and with reference to the accompanying

drawings, in which:

Fig. 1 is a schematic plan view of apparatus according to the invention in use for measuring an airframe;

Fig. 2 is a schematic view indicating how kinematic location may be provided;

Fig. 3 is a schematic perspective view of a pallet for use in an alternative embodiment as the rotary table of a CMM; and

Fig. 4 is a view similar to Fig. 3 of a further alternative embodiment.

The apparatus to be described in relation to Fig. 1 is for use in the calibration of measuring apparatus including a CMM 10 which determines the spatial relationship between the CMM 10 and a workpiece 12 such as an airframe. In view of the size of the airframe 12, relative movement between the CMM and airframe is provided by mounting the CMM on a movable pallet 14. The pallet 14 is movable to a plurality of measuring positions 16. Four positions 16 are shown in Fig. 1, and a pallet 14 is shown at each position, for convenience.

In practice, there may be considerably more positions 16, and only one position would normally be occupied by a pallet at any one time.

Six point kinematic location of the pallet 14 is provided at each of the positions 16, in the manner described in our co-pending application referred to above.

The apparatus further comprises second measuring apparatus to be described below and operable to determine the spatial relationship of the pallet 14 at its measuring positions 16 relative to a plurality of fixed positions 18, for the purposes of calibration.

The calibration apparatus operates by projecting laser beams between the fixed positions 18 and the pallet 14. The preferred arrangement is to use a laser tracker device to project the beam, and a retro-reflector device (hereafter referred to as a retro) to return the beam to the tracker. Suitable trackers and retros are known. The tracker device 20 may be located at one of the fixed positions 18, with the retro device 22 being mounted on the pallet 14, or the positions of the tracker 20 and retro 22 could be reversed.

A tracker 20 may be permanently located at each

fixed position 18. Alternatively, a single tracker device 20 could be provided, movable between the fixed positions 18, and having six point kinematic location at each position 18. Similarly, a single retro 22 could be permanently mounted on the pallet, but there are preferably provided three or more retros 22 mounted on the pallet 14, or means for moving a single retro 22 between three or more positions on the pallet 14, and for providing six point kinematic location of the retro 22 at each position on the pallet 14.

Kinematic location described above can be provided on the basis of the apparatus shown schematically in Fig. 2. True kinematic location requires point contact between two components, such as a sphere and a flat surface. In the example shown, a flat surface 30 is supported on the spherical tip 32 of a stalk 34. The stalk 34 is itself mounted on a fixed member 36 through a hinge portion 38.

The flat 30 is formed on a body 40 which may be the pallet 14. Six flats are provided on the pallet 14, and six stalks are provided in corresponding positions. In order to kinematically locate the pallet 14, the flats 30 are rested on the corresponding spheres 32, and a clamping mechanism (not shown) then clamps the pallet 14

down on to the stalks 34. In so doing, there may be slight relative movement of one or more sphere 32 in relation to its flat 30, possibly accompanied by small transverse movement of the stalk 34 on the hinge 38. By providing an accurately repeatable clamping force, this arrangement allows accurately repeatable kinematic location to be obtained as is described in more detail in our co-pending application, which also describes various alternative arrangements for providing kinematic location.

The apparatus shown in Fig. 1 can be used for calibration in the following manner. Firstly, the separation of the three points 24 is accurately measured, for instance by laser interferometry.

The pallet 14 is then located at one of the fixed positions 16, with the retro 22 at one of the three points 24, and the tracker 20 located at one of the fixed positions 18. A beam is established between the tracker 20 and the retro 22. The retro 22 is then moved to the other two points 24 in turn, without breaking the beam, to determine the spatial relationship of those two points relative to the first point 24. The tracker 20 is moved to another position 18 (without breaking the beam) and a further three measurements are taken by moving the retro

to the three points 24. Finally, three measurements are taken from the three points 24 with the tracker 20 at the third position 18. The whole process is then repeated for each of the measuring positions 16.

A large number of measurements would therefore be taken if all three fixed positions 18 are visible from all three points 24 when the pallet is in any of the measuring positions 16. In practice, especially when working with a large workpiece such as an airframe, it is unlikely that all of these measurements will be possible, but all measurements which are possible should preferably be taken. All possible measurements must be taken without breaking the beam, to ensure that they all relate to the same datum.

In the situation being described, it is necessary to have at least three fixed positions 18, and at least three points 24, so that at least six measurements can be taken at each pallet position 16. These can be, for instance, two measurements of each point 24 from different fixed positions 18. Other combinations are possible which fulfil the minimum requirement of six measurements at each position 16, of which there must be at least one from each point 24. If more measurements than the minimum can be taken, the results involve a

degree of redundancy which can be used to enhance the accuracy of the technique. In many practical situations, especially if the number of positions 18 or points 24 is increased, a high degree of redundancy is expected to be possible, resulting in accurate results.

Once these results are known, the apparatus can be considered to have been calibrated, because the pallet 14 can thereafter be moved back to the calculated positions with a high degree of repeatability, by virtue of the kinematic location used for the pallet.

Measurement of the workpiece can now begin. The pallet 14 is kinematically located at one of the measuring positions 16 and measures all accessible features of the airframe 12 from that position. The pallet 14 can then be moved to another position 16 for a second view of the workpiece to be taken. There may be as many measuring positions as required to provide an adequate number of views of the workpiece. The views taken from each of the positions 16 can be related to each other by virtue of the calibration, in order to provide an accurate overall measurement of the workpiece in a consistent co-ordinate system.

In moving the retro 22 around the pallet 14, as

described above, the technique is creating a notional article of known shape and size (determined by the layout of the three positions) fixed to the pallet 14. In a variation of the arrangement described above, and particularly applicable to a CMM with a rotary table, a physical artefact 50 (Fig. 3) may be fixedly mounted on the table 14 for calibration purposes. This may be a tetrahedron. Calibration then proceeds by taking measurements with the CMM (which acts from a fixed point) from at least three points 52 of the tetrahedron 50. The table is then rotated to a new position (and located there by kinematic location) and three more measurements are taken from the points 52, to determine the spatial relationship of the second table position in relation to the first. The process can be repeated for a large number of table positions.

Clearly, four measurements should be taken if possible, but many designs of CMM are likely to prevent more than three of the points being reached at any table position. The geometry of the tetrahedron is such that a physical artefact can be accurately described on the basis of solely linear measurements, so that the measurements taken at each table position can be related even if a different selection of points is measured at each.

A further alternative particularly applicable to a CMM with a rotary table is indicated schematically in Fig. 4. In this arrangement, the table (or pallet) 14 is provided with only one sphere 60 whose position can be measured by the CMM. Additionally, two mutually perpendicular level measuring means 62 are fixed on the pallet 14 to allow tilt of the pallet about two mutually perpendicular horizontal axes to be measured. In this arrangement, the single sphere 40 is sufficient to establish the linear relationship between two table positions, and the levels 62 allow two of the angular co-ordinates to be determined. The third angular co-ordinate (about the vertical axis) could be measured by conventional techniques such as the use of an auto-collimator, laser interferometer with angular option or other similar apparatus.

It will be understood that many variations and modifications may be made to the above apparatus without departing from the spirit and scope of the present invention. In particular, the apparatus for providing kinematic location, and the apparatus for determining the spatial relationship between the fixed positions and the pallet can all be changed according to operating requirements. The layout of the fixed positions and the measuring positions can be selected according to the

shape and size of the workpiece.

Claims:-

1. Apparatus for use in the calibration of measuring apparatus which determines the spatial relationship of two relatively movable components and which comprises means for moving one of the components relative to the other into a selected one of a plurality of measuring positions, and which further comprises means providing six point kinematic location of the movable components at each of the measuring positions, the calibration apparatus comprising a fixable article fixedly locatable on the movable component, the position of the fixable article being measurable in relation to a fixed position when the movable component occupies any of at least two of the measuring positions, to enable the spatial relationship of those measuring positions to be wholly or partially determined.

2. Apparatus according to Claim 1, wherein the position of the fixable article is measurable in relation to the same fixed points when the movable member is located at any of the measuring positions.

3. Apparatus according to Claim 1 or 2, wherein the fixable article is movable between a plurality of positions in relation to the movable component, and is

fixedly locatable in each of the said positions.

4. Apparatus according to any of Claims 1 to 3, wherein the fixed article is fixedly locatable on the movable component by means providing six point kinematic location.

5. Apparatus according to any of the preceding Claims, comprising second measuring apparatus operable to determine the spatial relationship of the or each fixed position and the fixable article.

6. Apparatus according to Claim 5, wherein the second measuring apparatus is operable to perform measurement by projecting a beam between the or each fixed position and fixable article when the movable component is located at a measuring position.

7. Apparatus according to Claim 6, wherein the beam is a laser beam.

8. Apparatus according to Claim 5, wherein the second measuring apparatus comprises a laser tracker device and a retro-reflector device for receiving a beam projected from the tracker device.

9. Apparatus according to Claim 5, wherein the second measuring apparatus comprises beam projecting means or beam receiving means movable between the fixed positions, the fixable article comprising beam receiving means or beam projecting means, respectively.

10. Apparatus according to any of the preceding Claims, further comprising means for establishing six point kinematic location of the beam projecting or receiving means at each of the fixed positions.

11. Apparatus according to any of the preceding Claims, wherein the measuring apparatus being calibrated is operable to provide measurements between the fixed position and the fixable article.

12. Apparatus according to Claim 11, wherein the fixable article is a calibration artefact defining a sufficient plurality of points for measurement to allow the spatial relation of the movable member and the fixed position to be determined by measurements taken between each point for measurement and the fixed position.

13. Apparatus according to Claim 12, wherein the calibration artefact defines four points for measurement.

14. Apparatus according to Claim 13, wherein the calibration artefact is a tetrahedron, defining a point for measurement at each apex.

15. Apparatus according to any of the preceding Claims, comprising level measuring means carried by the movable component and operable to measure rotation of the movable component about at least one horizontal axis.

16. Apparatus according to Claim 15, wherein the second measuring apparatus further comprises means operable to detect rotation of the movable component about a vertical axis.

17. Apparatus for use in the calibration of measuring apparatus which determine the spatial relationship between a fixed position and a plurality of points on the movable component defined by a fixable article or articles, the plurality of points being so located on the movable component that for each pair of adjacent measuring positions, there exists at least one point whose spatial relationship relative to the fixed position can be determined when the movable component is located at either measuring position, of the pair, whereby each measuring position may be calibrated with reference to a neighbouring measuring position.

18. Apparatus for use in the calibration of measuring apparatus substantially as hereinbefore described with reference to the accompanying drawings.

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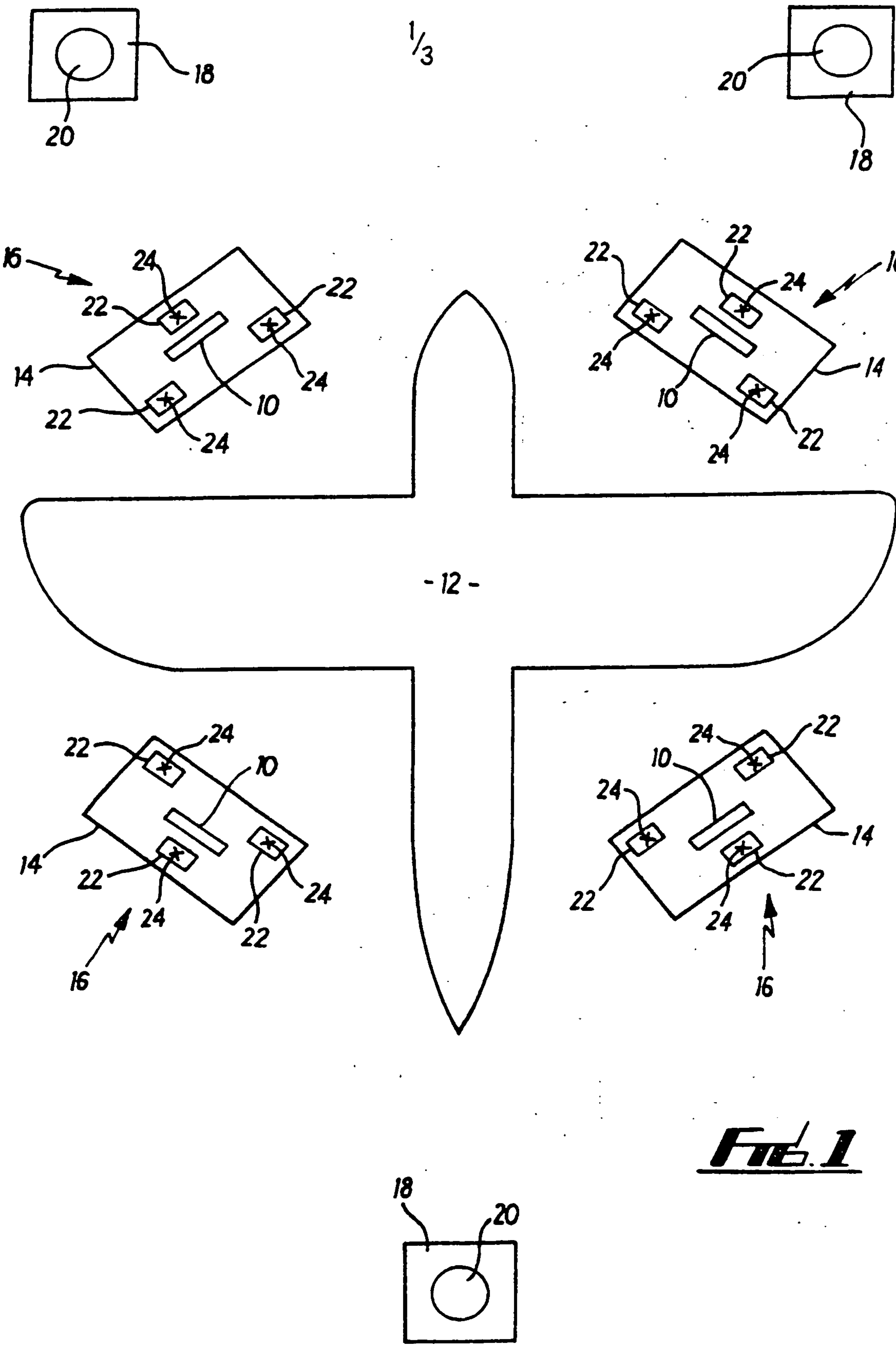

FIG. 1

SUBSTITUTE SHEET

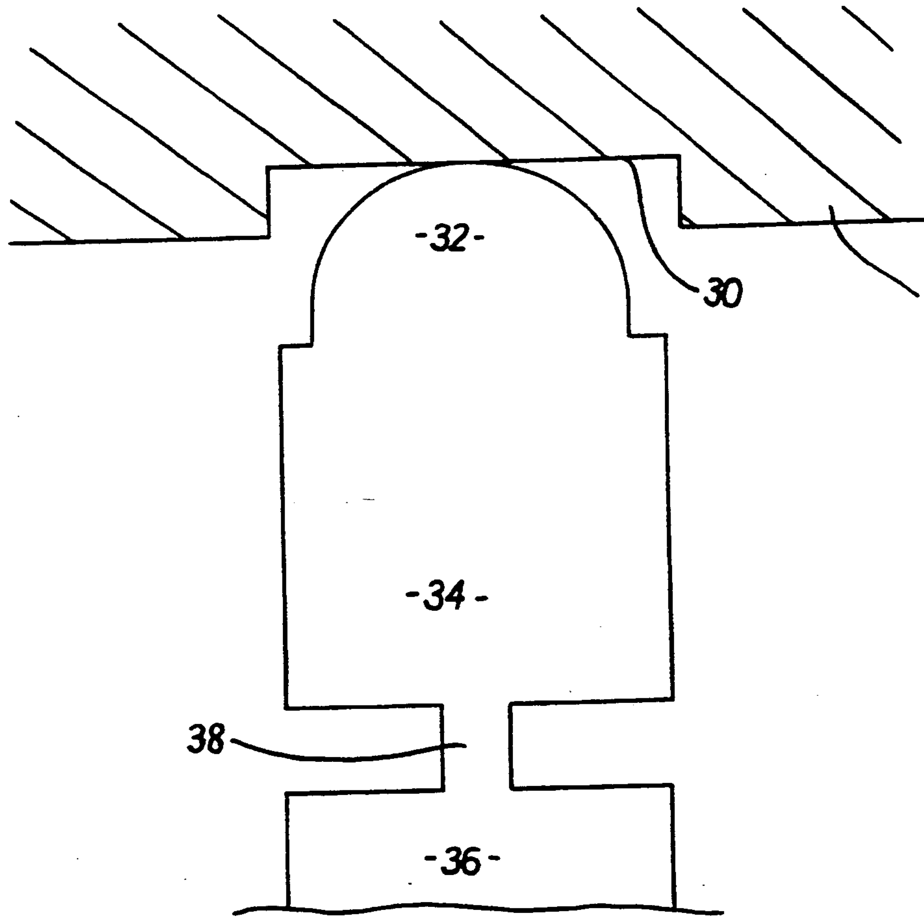

FIG. 2

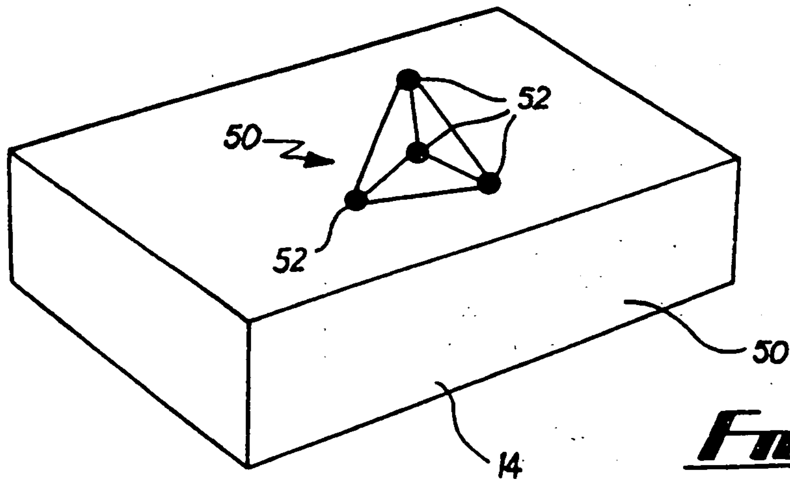

FIG. 3

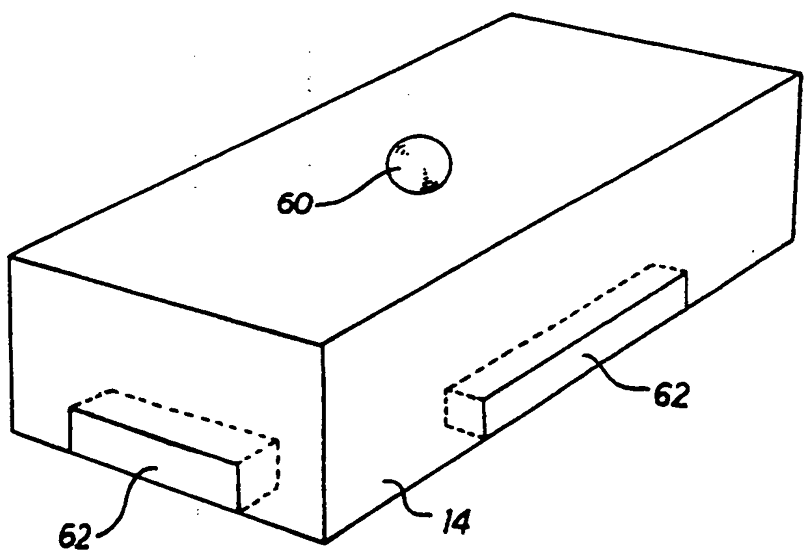

FIG. 4

INTERNATIONAL SEAR[blot]REPORT

International Application No PCT/GB 90/01618

I. CLASSIFICATION F SUBJECT MATTER (if several classification symbols apply, indicate all) [6]

According to International Patent Classification (IPC) or to both National Classification and IPC

IPC^5: G 01 B 11/00, G 01 B 21/04

II. FIELDS SEARCHED

Minimum Documentation Searched [7]

Classification System	Classification Symbols
IPC^5	G 01 B, G 01 C, G 01 S

Documentation Searched other than Minimum Documentation to the Extent that such Documents are included in the Fields Searched [8]

III. DOCUMENTS CONSIDERED TO BE RELEVANT [9]

Category *	Citation of Document, [11] with indication, where appropriate, of the relevant passages [12]	Relevant to Claim No. [13]
X,Y	Aircraft Engineering, volume 57, no. 8, August 1985, (London, GB), A. Lardelli: "ECDS1 - An electronic coordinate determination system for industrial applications", pages 2-5 see pages 2,3; figures 1,2,3; paragraphs 1-5 ---	1
X,Y	US, A, 4396945 (PAUL DIMATTEO et al.) 2 August 1983 see figures 1-3,5; introduction; column 2, line 14 - column 3, line 57; column 4, lines 38-59 ---	1-11,17, 18
Y	Onde Electrique, volume 65, no. 4, juillet-août 1985, (Paris, FR), M. Mayoud: "Géodésie et métrologie du LEP", pages 38-43 see paragraphs II, III; figures 2-6 --- ./.	1,15

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IV. CERTIFICATION

Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report
22nd January 1991	12 FEB 1991
International Searching Authority	Signature of Authorized Officer
EUROPEAN PATENT OFFICE	MISS T. TAZELAAR

Form PCT/ISA/210 (second sheet) (January 1985)

III. DOCUMENTS CONSIDERED TO BE RELEVANT (CONTINUED FROM THE SECOND SHEET)

Category *	Citation of Document, [11] with indication, where appropriate, of the relevant passages	Relevant to Claim No.
Y	Technische Rundschau, volume 80, no. 41, 7 October 1988, (Bern, CH), L. Nawara et al.: "Überprüfung von Koordinatenmessgeräten mit Normalen", pages 54-57, see pages 54-57; figures 1-3 ---	11-14
Y	US, A, 4639878 (C.P. DAY et al.) 27 January 1987 see introduction; figures 1-5; column 5, line 67 - column 8, line 60 ---	1,11-14
A	EP, A, 0143012 (SCIAKY S.A.) 29 May 1985 see introduction; figure 2; page 4, line 27 - page 6, line 26 ---	1
P,X	DE, C, 3833589 (H.H. SCHÜBLER) 15 March 1990 see introduction; column 2, line 22 - column 5, line 44; figures 1,2 ------------	1-11,17-18

ANNEX TO THE INTERNATIONAL SEARCH REPORT ON INTERNATIONAL PATENT APPLICATION NO. GB 9001618

SA 41219

This annex lists the patent family members relating to the patent documents cited in the above-mentioned international search report.
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Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US-A- 4396945	02-08-83	US-A- 4488173	11-12-84
US-A- 4639878	27-01-87	DE-A- 3618480	04-12-86
		JP-A- 62054115	09-03-87
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		CA-A- 1228922	03-11-87
		JP-A- 60149905	07-08-85
		US-A- 4651283	17-03-87
DE-C- 3833589	15-03-90	None	

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